The CALIPSO mission and initial results from CALIOP

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ABSTRACT

Satellite lidars are now beginning to provide new capabilities for global atmospheric sensing from space. Following the Lidar In-space Technology Experiment (LITE), which flew on the Space Shuttle in 1994, and the Geoscience Laser Altimeter System (GLAS), which launched in 2003, the CALIPSO satellite was launched on April 28, 2006. Carrying a two-wavelength polarization lidar along with two passive imagers, CALIPSO is now providing unique measurements to improve our understanding of the role of aerosols and clouds in the Earth's climate system. The primary instrument on CALIPSO is CALIOP (Cloud-Aerosol LIdar with Orthogonal Polarization), a two-wavelength polarization lidar. Using a linearly polarized laser and a polarization-sensitive receiver, the instrument allows the discrimination of cloud ice/water phase and the identification of non-spherical aerosols. First light was achieved in June, 2006 and five months of nearly continuous observations have now been acquired. Initial performance assessments and calibration activities have been performed and instrument performance appears to be excellent. CALIPSO was developed within the framework of a collaboration between NASA and CNES.

Keywords: atmospheric sensing, lidar, aerosols, clouds

1. INTRODUCTION

The CALIPSO satellite was launched on 28 April, 2006 and is now flying as part of the Afternoon Constellation (A-train)[1]. The CALIPSO mission was designed to provide unique measurements to improve our understanding of the role of aerosols and clouds in the Earth's climate system. CALIPSO carries the Cloud Aerosol LIdar with Orthogonal Polarization (CALIOP, pronounced as "calliope"), the first polarization lidar in orbit, along with infrared and visible passive imagers. The two imagers measure swaths of about 60 km, nominally centered on the lidar footprint.

CALIOP is a three-channel elastic-backscatter lidar optimized for aerosol and cloud profiling. Linearly polarized laser pulses are transmitted at 532 nm and 1064 nm. The 1064 nm receiver channel is polarization insensitive, while the two 532 nm channels separately measure the components of the 532 nm backscatter signal polarized parallel and perpendicular to the outgoing beam. Profiles from CALIOP provide information on the vertical distributions of aerosols and clouds, cloud ice/water phase (via the ratio of signals in two orthogonal polarization channels), and a qualitative classification of aerosol size (via the wavelength dependence of the backscatter).

The current A-train configuration consists of five satellites, all flying at an altitude of 705 km in a sun-synchronous polar orbit, with an equator crossing time of about 1:30 PM local solar time. CALIOP is a nadir-viewing instrument so it produces a curtain of profile data along the subsatellite point, providing sparse global coverage. The orbit inclination of 98^{o} provides coverage between 82^{o}N and 82^{o}S.

2. THE CALIOP INSTRUMENT

CALIOP consists of a laser transmitter subsystem and a receiver subsystem. The transmitter subsystem includes two identical, redundant laser transmitters, each with a beam expander, and a beam steering system that ensures alinement between the transmitter and receiver. The Nd:YAG lasers produce simultaneous pulses at 1064 nm and 532 nm at a pulse repetition rate of 20.16 Hz. Each laser generates 220 mJ of 1064 energy, which is frequency-doubled to produce 110 mJ of energy at each of the two wavelengths. The

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output pulse energy at each wavelength is measured using energy monitors located within each laser canister. The measured pulse energy is then used to correct the magnitude of the return signals for variations in magnitude due to changes in laser pulse energy. Key payload specifications are summarized in Table 1.

Table I. Key characteristics of CALIOP

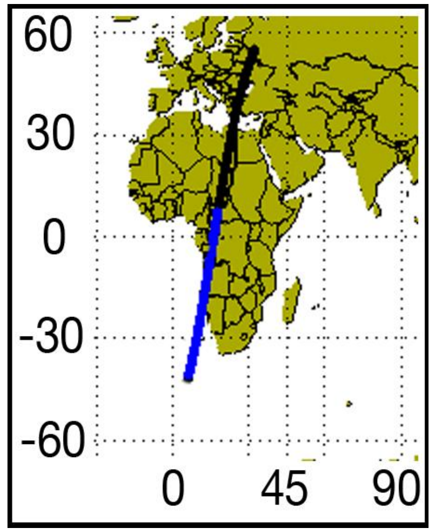
Laser	Nd:YAG
Laser Pulse Energy	110 mJ: 532 nm 110 mJ: 1064 nm
Laser Repetition Rate	20.16 Hz
Laser Pulse Length	20 nsec
Laser Polarization Purity	> 1000:1 (532 nm)
Receiver FOV	130 μrad
Vertical Sampling	10 MHz (15 m)
Footprint Spacing	333 m
Linear Dynamic Range (all three channels)	4E+6 : 1

A 1-meter telescope receives the backscattered light. Photomultiplier tubes (PMTs) are used for the 532 nm detectors as they provide very low dark noise and reasonable quantum efficiency. The sensitivity and large linear dynamic range of the PMTs allows measurement of molecular scattering in the stratosphere as well as signals from dense boundary layer clouds. An avalanche photodiode (APD) is used at 1064 nm as PMT detectors have poor quantum efficiency at that wavelength. The APD has good dynamic range and quantum efficiency but the dark noise is much larger than for the PMTs. Thus the 532 nm channels are more sensitive. A rotating mechanism allows a depolarizer to be moved into the 532 nm beam for depolarization calibration.

The backscattered signals are sampled at 10 MHz, corresponding to a 15 meter range increment. To match the bandwidth of the receiver electronics, the 532 nm channels are then averaged to 30-m resolution and the 1064 nm channel is averaged to 60-m resolution. To reduce requirements on downlink telemetry bandwidth, the lidar profile data is further averaged on-board the satellite prior to downlinking. To preserve the maximum amount of spatial information, only the upper portions of the profiles are averaged, according to the scheme shown in Table 2. Further details on the CALIOP instrument are given in [2]. Details on CALIOP retrieval algorithms and data products are given in [3].

Table 2. Spatial resolution of downlinked data.

Altitude Range (km)	Horizontal Resolution	Vertical Resolution	
		532 nm	1064 nm
30.1 to 40.0	5.0 km	300 m	---
20.2 to 30.1	1.67 km	180 m	180 m
8.2 to 20.2	1.0 km	60 m	60 m
-0.5 to 8.2	0.33 km	30 m	60 m
-2.0 to –0.5	0.33 km	300 m	300 m



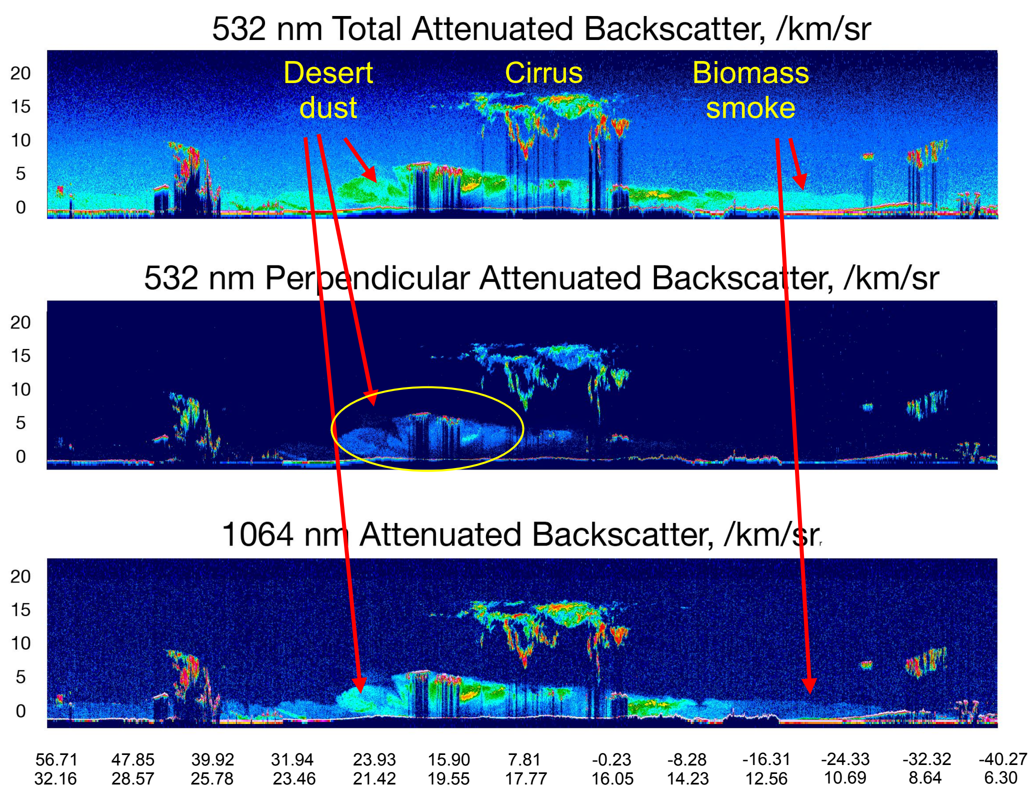


Figure 1. CALIOP observations from 9 June 2006, during the first week of on-orbit operation. The three panels show Level 1 data acquired along the orbit track shown in the map inset, from northern Europe across Africa into the south Atlantic. In the color coding scheme used in these panels, red represents strong returns from clouds and from the surface. Greens and yellows represent weak cloud and strong aerosol scattering, blues represent weak aerosol and molecular scattering. The middle panel indicates that depolarizing targets (cirrus and dust) produce a perpendicular return signal which is typically ¼ to ½ of the parallel return signal.

3. INITIAL OBSERVATIONS

CALIPSO was launched from Vandenburg AFB on 28 April and initially placed in a parking orbit at about 690 km altitude. The first few days after launch were spent bringing up the various spacecraft subsystems, stabilizing the satellite attitude and establishing communications. After confirmation of spacecraft health, the payload systems were brought up one by one. The first IIR images were obtained on 10 May and the first WFC images a few days later on 15 May. Following that, the laser receiver was powered on and an initial laser test was conducted on 23-24 May. The laser transmitter was not aligned with the receiver at this point, so no lidar profiles were obtained during this test. Payload operations were then interrupted for about a week while orbit maneuvers were performed to move the satellite into formation with the Aqua satellite.

Payload operations resumed in early June. The payload has an "alignment" mode, where the transmitter assembly is automatically scanned in two axes until a return signal is sensed. After the laser was again powered on, an alignment operation was performed and CALIOP 'first light' occurred on 7 June 2006. Figure 1 shows Level 1 data acquired a few days later. The figure shows data from all three lidar channels: 532 nm total and perpendicular attenuated backscatter, and 1064 nm total attenuated backscatter ("attenuated backscatter" is the calibrated return signal, not yet corrected for attenuation). The image shows a nighttime transect from northern Europe southward across Africa to the Atlantic Ocean. Inspection of these three images illustrates some of the capabilities of CALIPSO.

High cirrus is seen in the center of the image, located over tropical Africa. Black streaks indicate significant attenuation of the lidar signal, usually underneath optically thick clouds. The backscatter signal from the cirrus is similar at both wavelengths, which is characteristic of the relatively large cirrus particles. The cirrus is strongly depolarizing and produces a significant signal in the 532 nm perpendicular channel. Aerosol is observed everywhere beneath this cirrus, except for the most attenuating areas. To the south of the cirrus (on the right) is a smoke layer originating from biomass fires in southern Africa, which are widespread during this time of year. Part of the smoke layer is observed above a low stratiform cloud deck. Unlike the cirrus, this aerosol is weakly scattering at 1064 nm and non-depolarizing and produces negligible signal in the perpendicular channel.

The aerosol immediately to the north of the cirrus (toward the left), over the Sahara desert, is primarily dust. Dust particles are relatively large and irregular, so they also produce strong signals in the 1064 nm and perpendicular channels. The aerosol at the northern (left) edge of the figures is located over Europe. It is seen to be non-depolarizing and more weakly scattering at 1064 nm than the dust. This signature is indicative of secondary aerosol originating from anthropogenic activities.

4. ON-ORBIT PERFORMANCE

Part of the initial on-orbit activities was the assessment of instrument pointing biases and determination of the pointing of each instrument relative to the others. The satellite reference frame is nominally pointed forward 0.3^o in the along-track direction to avoid specular back-reflections of the lidar beam from ponds and other still water. Satellite pointing is determined from analysis of attitude and ephemeris data. Pointing biases of the instruments with respect to the satellite are determined by comparison of predicted instrument footprint and pixel locations with known surface features. Lidar pointing is detemined by comparison of surface topography with a Digital Elevation Map (DEM). Regions of high surface relief are selected and the predicted lidar footprint locations are shifted to provide the best correlation with the DEM topography. The amount of shift required provides a measure of the instantaneous pointing bias. This procedure is repeated over a period of time and at different locations around the globe to assess spatial and temporal stability of the pointing. A similar approach is used for assessing imager pointing, except that identifiable surface features such as coastlines, islands, and airport landing strips are used in place of surface elevation.

Results are shown in Figure 2. The attitude control system on the satellite causes the lidar footprint to trace out a figure-eight pattern around the satellite geodetic nadir vector. During the course of an orbit, the footprint moves about ±300 meters in the along-track direction and ±75 meters in the cross-track direction, relative to the nadir point. The nominal position of the lidar footprint is located about 55 meters to the west of the nadir ground track. The dashed circle shows the pointing control required to meet mission requirements. It can be seen that pointing performance meets requirements with quite a bit of margin. The center pixel of the IIR is located 750 meters forward and 1000 meters to the east of the lidar footprint. The center pixel of the WFC is located 550 meters forward and 450 meters to the east of the lidar footprint. The magnitude of these biases does not present any problems, as long as they are known accurately, as the lidar footprint lies well within the swaths of the two imagers. On-going assessments of instrument pointing are underway, to monitor any potential drifts in these pointing biases.

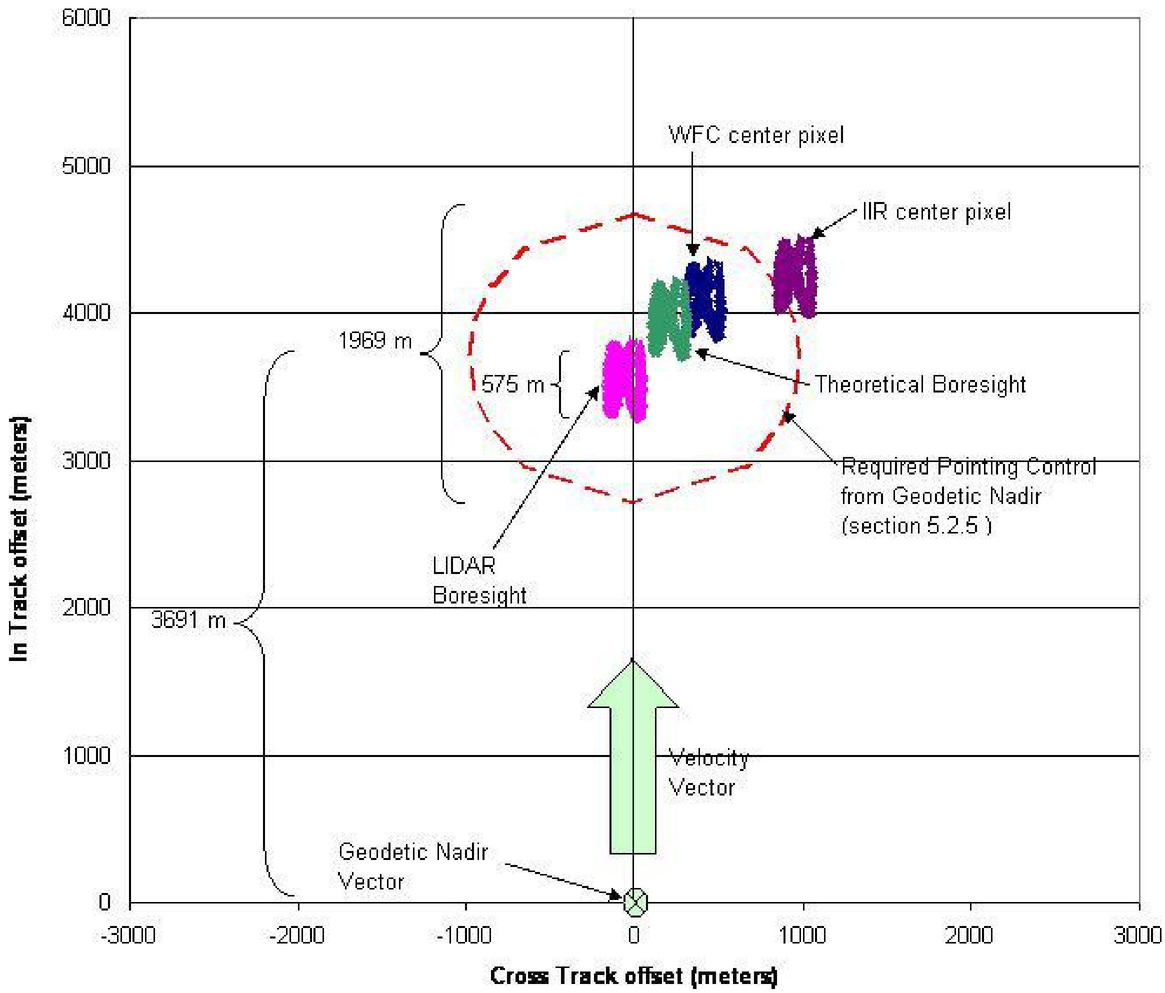


Figure 2. Pointing biases of the three instruments relative to the satellite geodetic nadir point. The satellite attitude control system causes the instrument footprints to trace out a figure-eight pattern during the course of an orbit.

As this is written, CALIOP is approaching five months of near-continuous operation, and initial assessments indicate excellent on-orbit performance. Laser 2 has been used exclusively since the beginning of the on-orbit mission. Figure 3 shows the time series of pulse energy since the initial turn-on, during which about 260 million shots have been generated. Initially, differences between the ground and on-orbit environments caused the 532 nm pulse energy to be slightly high and the 1064 nm energy to be slightly low. During the first week of operations, adjustments were made to the laser temperature and pump energy to bring the pulse energy at both wavelengths to near 115 mJ. Since then, pulse energies have been relatively stable. The lasers are built as power oscillators, with a single Nd:YAG slab pumped by 192 diode bars[2]. Sudden drops of about ¾ mJ were seen at each wavelength after about 40 days and again after about 80 days of operation. These events are believed to be due to diode bar dropouts, a phenomena which has also been observed on ICESat[4] and MOLA, two satellites which have flown lasers using pump diodes similar to those used in CALIOP. In addition to these sudden drops, there is a slowly decreasing trend of about 0.02 mJ/day throughout much of the 5 months. The cause of this trend is not understood, but it has leveled out recently and the pulse energy has recently been very stable.

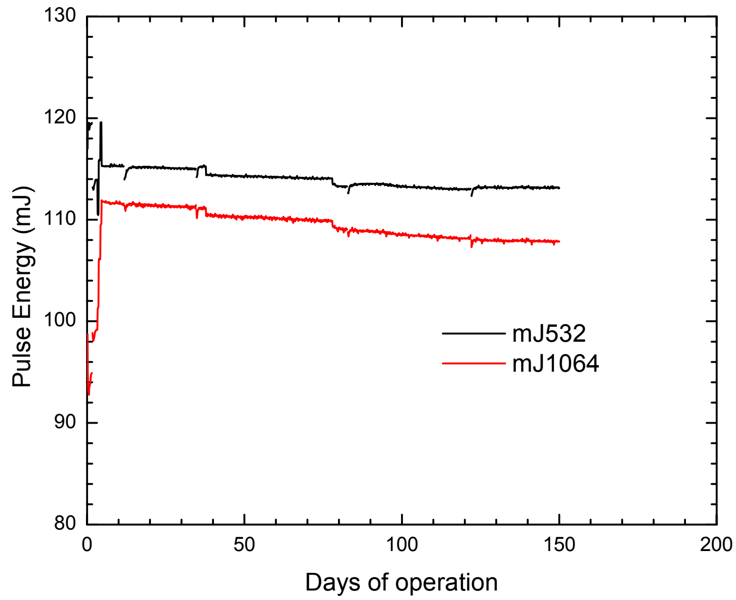


Figure 3. On-orbit time series of laser 2 pulse energy over the first five months of operation.

Figure 4 compares a highly averaged atmospheric profile from the CALIOP 532 nm parallel channel with the signal predicted from a purely molecular atmosphere. The observed profile represents an along-track average over about 8000 km, to improve SNR, and is free of aerosols and clouds above 18 km. Variability in the profile below 18 km is due to the presence of various cloud and aerosol layers The comparison above 18 km shows the observed high altitude signal strength is about 30% greater than predicted by the instrument performance model, probably due to an overestimate of optical transmission losses in the model. The SNR of the high altitude portion of this profile was also found to be somewhat higher than expected, indicating no unexpected sources of excess noise. These results confirm that the sensitivity of the 532 nm parallel channel meets expectations in terms of signal strength and SNR. Similar results have confirmed the sensitivity of the 532 nm perpendicular channel and the 1064 nm channel.

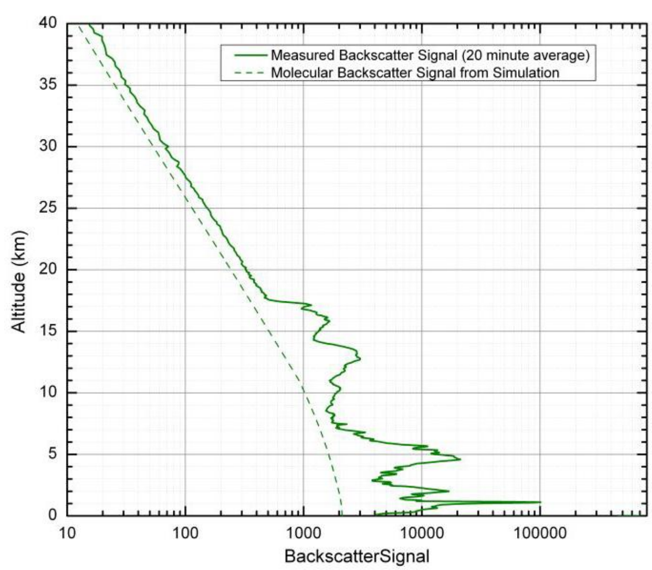


Figure 4. Comparison of averaged on-orbit profile from the 532 nm parallel channel with signal strength predicted by the CALIOP instrument performance model assuming a purely molecular atmosphere.

5. CALIBRATION

CALIOP is calibrated in three steps:

1) The 532 nm parallel channel signal is normalized to the predicted molecular volume backscatter coefficient in the 30-34 km region[6]. The molecular backscatter coefficient is estimated using temperature and pressure profiles from a gridded meteorological analysis product. The uncertainty in this estimated molecular backscatter coefficient is estimated to be 3%[5]. The 30-34 km region was chosen because the aerosol backscatter in that region is small relative to molecular backscatter. The parallel-polarized component of the molecular 180^{o}-backscatter is derived from the estimate of total molecular 180^{o}-backscatter by taking into account the bandwidth of the receiver optical filters. Independent estimates of the 532-nm parallel channel calibration constant are computed at approximately 700-km intervals over the dark side of each orbit and interpolated to the day side.

2) The calibration of the 532-nm parallel channel is transferred to the 532-nm perpendicular channel via insertion of a pseudo-depolarizer in the receiver optical path. The pseudo-depolarizer ensures that, regardless of the polarization state of the backscatter incident on the receiver, an equal amount of light is sent to the parallel and perpendicular channels of the receiver downstream of the depolarizer. The pseudo-depolarizer is inserted periodically during the mission, to track any relative change in sensitivity of the parallel and perpendicular channel detectors.

3) The calibration of the 532-nm channels is transferred to the 1064-nm channel via comparison of the return signals from high-altitude cirrus clouds[5] Cirrus cloud particles are large compared to the transmitted wavelengths, so the backscatter coefficients will be nearly equal at 532 nm and 1064 nm. By choosing clouds for which the ratio of particulate to molecular scattering is 50 and above, the calibration can be transferred with high accuracy.

Thus, the accuracy of the calibration of the 532-nm perpendicular and 1064-nm channels depends on the calibration accuracy of the 532-nm parallel channel. The 532-nm parallel calibration coefficient is computed using the range-, energy-, and gain-normalized return signal, *X(r):*

$$X(r) = r^2 P(r)/EG,$$

where *P(r)* is the background-subtracted raw signal at range *r, E* is the measured laser pulse energy, and *G* is the electronic gain of the receiver channel. *X(r)* is essentially the uncalibrated attenuated backscatter signal. *X(r)* is averaged over the 30-34 km altitude range and over 165 adjacent profiles, and the calibration coefficient, $C_{532,}$ is obtained by dividing this average by the mean attenuated backscatter coefficient (/km/sr) predicted for a molecular atmosphere so that one calibration value is obtained for each 55 km along track.

Because the return signal from the 30-34 km region is very weak, these 55-km averages are still relatively noisy. Figure 5 shows the result of further averaging these 55-km averages. The data represented here is from about 140 nighttime orbit segments acquired over the western Pacific Ocean during a two week period. Each data point is the average of the C532 values along one orbit track between 30^{o}N and 30^{o}S. The RMS variability of the points is about 1.1%. This value is just a little larger than the variability expected from photon noise alone and also includes any variability due to errors in the gridded pressure and temperature profiles being used, giving an indication of the stability of the instrument and the utility of this method of calibrating the instrument.

6. SUMMARY

CALIOP is the second polar-orbiting lidar to fly in Earth orbit. It is the first satellite polarization lidar and the first satellite lidar designed primarily for study of the atmosphere. After five months of nearly continuous on-orbit operation, the laser appears to be healthy and all payload and spacecraft systems are functioning well. The data acquired during this period already constitutes a unique and important dataset and enables many new research opportunities. CALIPSO is flying in formation with the A-train constellation of satellites. Investigations making use of CALIPSO data on its own and in combination with other A-train observations hold the promise of opening a new era in our understanding of the role of aerosols and clouds in the global atmosphere.

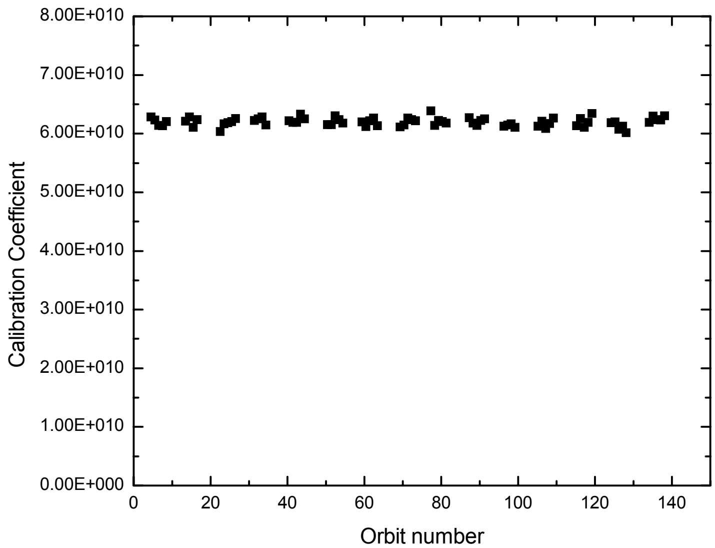


Figure 5. Averaged calibration coefficients for the 532-nm parallel channel derived from CALIOP profiles acquired in a two week period over the tropical western Pacific.

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